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Modelling barriers to low-carbon technologies in energy system analysis: The example of renewable heat in Ireland

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ABSTRACT

While there is a rich body of literature on the wide range of barriers to investment in renewable energy technologies, little guidance exists on how to integrate the barriers into energy systems modelling. The present study develops a prototype to represent barriers such as risk perceptions and inertia in energy systems analysis. Employing a techno-economic model that describes the deployment of renewable heating technologies in Ireland, our results show the methodological importance of the representation of heat-users' decision making process in energy systems analysis. Implications in promoting renewable heat, market development and regulation are discussed.

1. Introduction

Europe is facing an unprecedented energy and climate crisis, yet it may represent an opportunity to increase necessary efforts to accelerate the energy transition and enhance its energy autonomy. Despite the steady progress in renewables, the latest data show that fossil fuels still remain the largest source of heat production in the European Union (EU) [1]. Particularly, fossil gas plays the dominant role in heat production, and in recent years remains stable, supplying nearly 40% of heat production. Solid fossil fuels, previously the second largest source of heat production, was surpassed by renewables in 2015. With the long-term vision for a climate neutral Europe, decarbonization in the heating sector deserves close attention to reduce its dependency on fossil fuels.

The heating sector has experienced relatively few attempts to promote renewable technologies compared to the power and transport sectors. This reflects a range of challenges facing the heating sector, such as the fragmented nature of the heat market, the difficulties of retrofitting existing buildings with new heat technologies, the complexities of biomass fuel supply, and the administrative difficulties of implementing policy support for renewable heat. While most European countries have support schemes to encourage the development of renewable electricity, dedicated policy supports for the uptake of renewable heating systems are less prevalent [2,3]. Where supports exist, renewable heating technologies are often included as part of energy efficiency programmes, and financial supports and low-interest loans are provided to heating technology investors with the aim of energy efficiency improvement [4,5]. Energy efficiency programmes are considered to be more straightforward to implement with palatable costs than renewable heat programmes, as heat is difficult to metre or produce at large scale and transport over significant distances in an efficient way.

Energy systems models are mathematical tools developed to represent various energy-related issues, and have been frequently used to explore future energy demand scenarios and to support the decision-making regarding energy transitions [6–8]. Despite the efforts to mirror the real-world conditions as closely as possible, many existing energy systems models tend to model the barriers to energy efficiency investments in a rather aggregated way. As an EU-wide energy systems model in support of EU policy making, PRIMES (Price-Induced Market Equilibrium System) considers behaviour-related barriers by employing adjusted discount rates and imposing additional constraints on the deployment of energy efficiency technologies [9]. Modified discount rates are also employed in TIAM-UCL Global Model and EFDA-TIMES Global Model to reflect risks facing different sectors and geographic regions [10]. Few studies have explicitly clarified the methodology to integrate behavioural barriers but their models tend to consider only a fraction of the barriers (e.g. [11,12]). This current work demonstrates that the specific implementations of decision-making processes and the

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Abbreviations

AD CHP	Anaerobic digestion combined heat and power
ASHP	Air source heat pump
CHP	Combined heat and power
EU	European Union
GHG	Greenhouse gases
GSHP	Ground source heat pump
GWh	Gigawatt hours
PRIMES	PRice Induced Market Equilibrium System
WSHP	Water source heat pump

incorporation of behavioural barriers within energy models can lead to substantially different modelling outcomes, for example, in terms of projections of technology adoption. Consequently, policy implications derived from these models may differ substantially even based on the same underlying data. Where models such as PRIMES that are closely integrated into the EU's policy making process are already criticized for lack of transparency (e.g. [13–15]), this current work additionally questions the robustness and validity of energy system models that implement the barriers and decisions surrounding technology adoption in a superficial manner.

The contribution of the present study is two-fold. First, our study contributes to deepening the understanding on how to translate economic and behavioural barriers to energy efficiency into modelling elements. Although there is general agreement that behavioural barriers, such as bounded rationality and inertia, play a significant role in the deployment of energy efficiency technologies, they are not well reflected in existing energy system models. By aligning the barriers identified in the literature with elements of a recently developed energy systems model, we aim to narrow this research gap by demonstrating the importance of incorporating behavioural and economic barriers into energy scenario analyses. Understanding the impacts of these barriers on the uptake of renewable heating technologies is of key importance to accelerate the low-carbon transition of the sector. Our results show that the inclusion of behavioural barriers, including implicit financial considerations, and how they are represented can have significant impacts on modelled outcomes.

Second, the present study draws attention to heat decarbonization and the deployment of low-carbon heating technologies that to date have been underrepresented in energy systems modelling literature. Though energy use for heating and cooling accounts for more than half of global final energy consumption, the heating sector tends to be neglected and analysed at an aggregated level. With the long-term vision for carbon neutrality, decarbonization in the heating sector deserves close attention. Furthermore, the present study contributes to improving the transparency and openness of energy systems models. Decisions on energy policies are often supported by modelling results but in many instances the underlying models are not easily accessible for scrutiny.

To demonstrate our approach, we build upon the BioHEAT model of Durusut et al. [16] and demonstrate the rich functionalities of better modelling investors' decision-making processes. Compared to Durusut et al. [16] the novelty of the present study lies in the special attention devoted to the linkage between the existing literature on barriers to energy efficiency investments and the application of barrier integration in practice. Moreover, we equip the model with two types of discounted payback methods motivated by the minimum acceptable rate of return and the discounted cash flows. This enables us to analyse the impacts and importance of the barriers' representation in detail.

With a focus on bioenergy supply chains in Ireland, we show explicitly how the integration of behavioural and non-financial barriers in energy systems models has a large impact on model outputs. Policy recommendations underpinned by analysis from the model are provided. Barriers to energy efficiency investments are embedded within six measures: (A) using a detailed representation of building stock, (B) including hidden monetary costs in the payback calculation, (C) including decision-makers' budget constraints, (D) incorporating decision-making frequency, (E) and the percentage of laggards, plus (F) using a payback analysis with alternative capital budgeting rules. We measure the impact of behavioural barriers on the uptake of advanced heating technologies by changing the aforementioned elements within the BioHEAT model. By comparing the variations in projections associated with the inclusion of different barriers the present study suggests that in our setting the behavioural barriers have at least comparable, or more likely larger, influence on projected model outcomes than financial barriers. Different measures affect the deployment of technologies and heat user sectors to different extents. Under the current modelling assumptions, the public sector is the most sensitive to discounted payback calculation, while the residential sector is the least affected by discounted payback calculation.

The article is organized as follows. Section 2 overviews financial and non-financial barriers to the adoption of energy efficiency technologies, and how they are captured in typical energy systems models. Section 3 presents the methodology of BioHEAT, the incorporation of barriers and the discounting approaches. Section 4 presents the results of scenario analyses conditional on different barriers. The last section summarizes the findings and discusses policy implications.

2. Barriers to energy efficiency measures and the representation in energy systems smodelling

Despite the present focus on renewable heating technologies, there is an extensive literature investigating barriers to energy efficiency investments in general. In this section we conduct a brief overview of studies on barriers to energy efficiency investments where heating technologies are included. Public, commercial, and manufacturing decision-makers are the primary focus of the review because of their relatively high purchasing power, although most of the barriers also apply to households. We then identify the methods utilized to incorporate behavioural barriers in existing representative energy systems models.

2.1. Barriers to energy efficiency in the literature

Barriers to energy efficiency measures have been discussed extensively in the literature. Studies such as Sorrell et al. [17], Fleiter et al. [13] and Gupta et al. [18] provide systematic reviews on the topic. Seminal contributions were made by researchers from Sussex Energy Group at the University of Sussex who developed a taxonomy consisting of three broad categories: economic, behavioural, and organizational barriers. This framework has been widely cited in the literature (e.g. [19–25]). Based on the framework proposed by Sorrell et al. [17,26, 27], Table 1 presents a summary of the barriers categorized into three groups, namely economic, behavioural and organizational barriers. Illustrative examples regarding heating technologies are provided in the last column. Barriers range from specific temperature requirements for production purposes to the level of risk aversion of an individual. Very often multiple barriers act together to deter investors from choosing renewable heating technologies. Heterogeneity, hidden costs, access to capital, risks and uncertainties, and bounded rationality are the most widely mentioned in the literature.

Heterogeneity — Heating demand is complex and can vary greatly across regions due to climate, building conditions and occupancy. Thermal and climatic factors (e.g. insulation level, thermal needs, heating degree days) are crucial parameters to take into account when choosing a heating system [29,30]. Certain innovative heating technologies may not be able to fulfil industrial heat requirements such as temperature,

Table 1
Barriers to renewable heating technologies facing non-residential investors.
Source: Authors' elaboration based on Sorrell et al. [26], Rohdin and Thollander [19] and Schleich [28].

Categories	Barriers	Examples
Economic barriers	Heterogeneity	Renewable heat options may not be cost-effective in some buildings, e.g. under poor isolation conditions
	Hidden costs	May include search costs associated with gathering and assimilating information; retrofit installation of renewable heat systems may entail production disruption; renewable technologies often require more space and can result in higher maintenance requirements
	Access to capital	Limited access to affordable finance and capital may prevent investment on renewable heat investment; high capital costs than fossil fuel alternatives; lower-than-efficient energy prices
	Risks	Risk aversion may be the reason why renewable heat options are constrained by short pay-back criteria; lack of confidence in renewable heat technologies
	Imperfect information	Lack of information may lead to cost-effective energy efficiency measures opportunities being missed, e.g. lack of knowledge on subsidies or tax incentives
	Split incentives	The potential investor on energy efficiency measures is not the party that pays the energy bill, e.g. building owner and occupier/tenant
	Adverse selection	Producers and suppliers of energy-efficient equipments are in general more informed about the products than purchasers. The purchasers may select products based on visible aspects e.g. prices instead of quality
	Principal–agent relationships	The owner of a company may not be as well-informed as the executive about the site-specific conditions for energy efficiency investments, and may prefer short payback investments
Behavioural barriers	Bounded rationality	Instead of being based on perfect information, decisions are made by rule of thumb
	Form of information	Information should be specific, vivid, simple, and personal to increase its changes of being accepted
	Credibility and trust	The information source should be credible and trustworthy in order to successfully deliver the information
	Inertia	Individuals may be opponents to change and prefer replacement with the same technology (e.g. fossil fuel)
	Values	Energy cost saving measures are not as valuable as measures that improve productivity
Organizational barriers	Power	Low status of energy management may lead to lower priority of energy issues within organizations
	Culture	Decision makers may decide to implement significant energy efficiency measures because of high level of environmental concerns

pressure and quantity of heat [31]. For some renewable technologies it can be challenging to meet the EU emissions and sustainability criteria, such as the example of small-scale biomass combustors [32]. For technologies such as heat pumps that consume electricity, the net emissions saving depends on the electricity mix of a country [33].

Hidden costs — Hidden costs may arise during all stages of the uptake of renewable heating technologies. Potential costs are associated with gathering and assimilating information regarding product quality, costs of specification, tendering and bargaining. Replacing existing heating systems can cause heating and production disruptions, which may be a particularly pertinent issue for hotels and manufacturers; the installation of ground-source heat pumps requires flooring and garden work. For biomass boilers, large physical spaces are required for fuel storage, as well as continuous maintenance effort and time spent in fuel delivery and ash handling. All these inconveniences and indirect costs can lead to substantial deviations from economically optimal heating options [27,34–36]. The table in the appendix presents further details on the calculation of hidden costs.

Access to capital — Potential adopters may simply lack access to the capital needed to invest in advanced heating systems. At the decision-maker level, investment decisions depend on their economic situation, thereby social democratic features play a role in influencing the choice [34]. Company characteristics such as number of employees or floor area can influence decision making in energy efficiency investments. Moreover, since the cost of capital also reflect risks associated with the borrower, small businesses are often subject to higher risk premiums and borrowing costs [21,37].

Risks — Certain renewable heating systems are less commercially mature compared to conventional options, implying a reduced certainty concerning long-term competitiveness. At the early stage of market development, building a supply chain network for biomass fuels can be costly due to lack of economies of scale. Risks associated with fuel supply are likely to be even more detrimental, appearing across the whole supply chain from harvesting and collection of domestic fuel, import and transportation of international resources, to distribution, sales, and the availability of qualified technicians for installation and maintenance. A limited number of biomass suppliers can significantly affect the risk perception of potential adopters in terms of the reliability of supply, prices and quality. Furthermore, biomass fuels are often characterized by seasonality and harvested at a certain time of the year (e.g. willow, grass), while the demand is likely to be on a year-round basis [38]. Extreme weather events potentially add further uncertainties to biomass supply chains. As the demand for biomass continues to grow, biomass import from third countries may play a role in decarbonizing the heating sector. In such cases both the availability and the cost of imported biomass will depend on international markets, which leads to extra uncertainty on biomass costs and supply [39].

Bounded rationality — Instead of searching for optimal decisions, investors with bounded rationality make satisfactory decisions based on imprecise routines and rules of thumb [21,22]. When an existing boiler breaks down, a solution is usually needed at short notice. In this case an investor may prefer replacement with the same heating system. For non-residential investors, decision making is likely to be a pre-defined process involving complex budgeting rules. On the one hand, institutionalized decision making is likely to gather more information than individuals and such expertise accumulation can help to contribute towards economically rational decisions [40]. On the other hand, firms may have spending priorities other then saving energy. If energy costs only account for a marginal proportion of firms' overall operating cost, investments on energy efficiency is unlikely to bring significant benefit to firms' turnover. Therefore, firms are less likely to invest in energy efficiency measures. Employing data from the U.S. and the Europe, Qiu et al. [41] and Nehler and Rasmussen [42] show that activities related directly to SMEs' core business, such as productivity improvements, have significantly higher chances of being funded compared to similar investments offering only energy savings. Firms tend to apply excessively high discount rates to evaluate energy efficiency investments, despite the fact that energy efficiency investments do not share the company's risk profile and the investment amount is relatively small [41]. Even if non-energy benefits are recognized by firms, there is a lack of knowledge of how these should be quantified and monetized [42]. Moreover, idiosyncratic characteristics of individual firms, such as preferences for large cash holdings, or bureaucratic and organizational procedures, can all lead to divergence from optimal decision making [43–45].

2.2. The representation of barriers in energy systems models

While past work has demonstrated the existence of various barriers to technology adoption, most existing energy models incorporate the barriers in a rather aggregated way, and only a few of the observed barriers are explicitly considered. To reflect the respective behaviour of agents in investments, an adjusted discounting approach has been employed in several large-scale bottom-up energy systems models.[1] The PRice Induced Market Equilibrium System (PRIMES) is one such model. Employed by the European Commission in developing EU climate and energy policies, PRIMES describes the entire energy system of the EU from primary energy supply to end-use sectors [48,49]. Sector agents make decisions on whether to purchase equipment, invest in energy-saving measures, or fund infrastructure by selecting across several alternative technologies featuring different upfront costs and variable operating costs [9,50,51].

Within PRIMES subjective discount rates play a critical role in modelled outcomes and are intended to capture uncertainties facing investors. The rationale is that on top of financial considerations, sector-subjective discount rates reflect the relative behaviours of investors in different sectors in the adoption of new technologies. The rates vary by sector and technology: households are assumed to use higher discount rates than industries where large companies are involved; risk premiums of 1%–3% are applied to immature technologies or technologies with low market penetration to reflect the barriers that hamper the diffusion of technologies [49]. In the EU Reference Scenarios 2016, PRIMES includes six energy supply sectors (discount rates ranging from 7.5%–8.5%), six energy demand sectors (7.5%–11%), and three types of households (11%–14.75%).[2] A number of other models also employ subjective discount rates to reflect uncertainties, and the rates are largely in line with those in PRIMES. For example, the ETSAP-TIAM model is a global multi-regional model that builds low-carbon energy scenarios. It employs a hurdle rate of 10% to evaluate the investments in heating measures [52]. Within the same model family, TIAM-UCL Global and EFDA-TIMES Global employ a discount rate of 10% for investment decisions in industry sector, and 15% for those in commercial and residential sector [10,53]. Another example is the JRC-EU-TIMES model that uses discount rates of 17%, 14%, 12% for residential, large industry, and small industry and commercial sector respectively [54].[3] Overall, subjective discount rates are the only way these models incorporate the risk and barriers in decision making process.

A few bottom-up models have considered barriers to energy efficiency investments using methods other than subjective discount rates. A recent extension of PRIMES, namely PRIMES-BuiMo, considers energy efficiency investments in EU residential and service buildings. Hidden costs are considered explicitly by including perceived costs of technologies in the calculation of investment costs to reflect non-market barriers [61,62]. Access to capital is also considered partially in PRIMES-BuiMo by employing subjective discount rates across different income groups. Other advanced models in respect of barriers representation include CIMS and SAVE Production. CIMS is a hybrid energy-economy model that combines characteristics of top-down and bottom-up energy systems models [11,63]. Besides implicit discount rates to reveal the real-world technology adoption process, CIMS includes intangible costs that consumers and businesses perceive. SAVE Production is a bottom-up techno-economic model designed for the Dutch energy system [12]. It considers risks captured by discount rates and also the psychological effects stemming from energy price changes and policy stringency in the form of a loading factor. PRIMES-BuiMo, CIMS and SAVE Production are considered to be the most advanced models in terms of barrier realism. However, only a limited number of barriers are factored into the model, including hidden costs and risks, nor are there clear instructions on the formation of risk premiums or perceived costs. This highlights the limited public access to the technological details of energy systems models. The factors behind the discount rates and their respective implications for policy making remain blurred. Hermelink and de Jager [14] and Earl et al. [15] appraise the PRIMES model, both of which suggest a lack of transparency associated with the determination of the discount rates. Without a common understanding on how to translate economic and behavioural barriers into energy systems models, the high discount rates may affect the ambition on energy efficiency targets as high discount rates signals that energy efficiency investments are less attractive financially.

3. Methodology

To demonstrate the importance of how technology adoption is integrated in energy systems modelling, we employ the BioHEAT model that describes the supply and demand of bioenergy in Ireland [16]. The model is maintained by the Sustainable Energy Authority of Ireland, and has recently been applied in the development of Ireland's energy and greenhouse gas emissions projections [64]. We briefly illustrate the structure of BioHEAT in Section 3.1, and present the extension to the discounting in the investment evaluation in Section 3.2.

3.1. BioHEAT model and the representation of barriers

BioHEAT covers three energy demand sectors (power, transport and heat) and four heat demand subsectors (residential, commercial, public and industry). Heat demand and supply are mapped in five steps as shown in Fig. 1: (1) calculating the costs of bioenergy pathways based on biomass supply curves and cost data on transport, refining, technology and fuel prices; (2) identifying least-cost ways to meet bioenergy demand in transport and power; (3) calculating the uptake of advanced heating technologies in heat demand subsectors; (4) setting the priority

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[1] Adjusted discount rates are sometimes called subjective discount rates in the literature, and we use them interchangeably in the present study. It is noteworthy that discount rates discussed in the present study are financial discount rates used in private investment appraisals, in contrast to social discount rates that reflect the society's view on how future benefits as well as costs are valued against present ones. In practice, social discount rate is used to aggregate system-wide costs over multiple periods in order to compare scenario performances. Financial interest rates are used by decision makers to annualize investment expenditures and to compare alternatives from a private perspective. European Commission recommends the majority of Member States employ a 3% social discount rate and 3%–6% financial discount rates on cost–benefit analyses of major investments up to 2020 [46,47].

[2] A full list of the subjective discount rates used in PRIMES can be found in Capros et al. [49].

[3] Besides the aforementioned models, we conduct a search of documentation and manuals of the 16 energy systems models listed in Fattahi et al. [55] and find assumptions on discount rates for just four models. Specifically, NEMS employs technology-specific discount rates ranging from 15% to 90% for residential and commercial sectors [56,57]. IWES employs a rate of 3.5% for heating appliances, 5.7% for networks, and 5.8%–11% for generating plants [58]. OSeMOSYS and ESME use single rates of 5% and 8% respectively for all sectors [59,60].

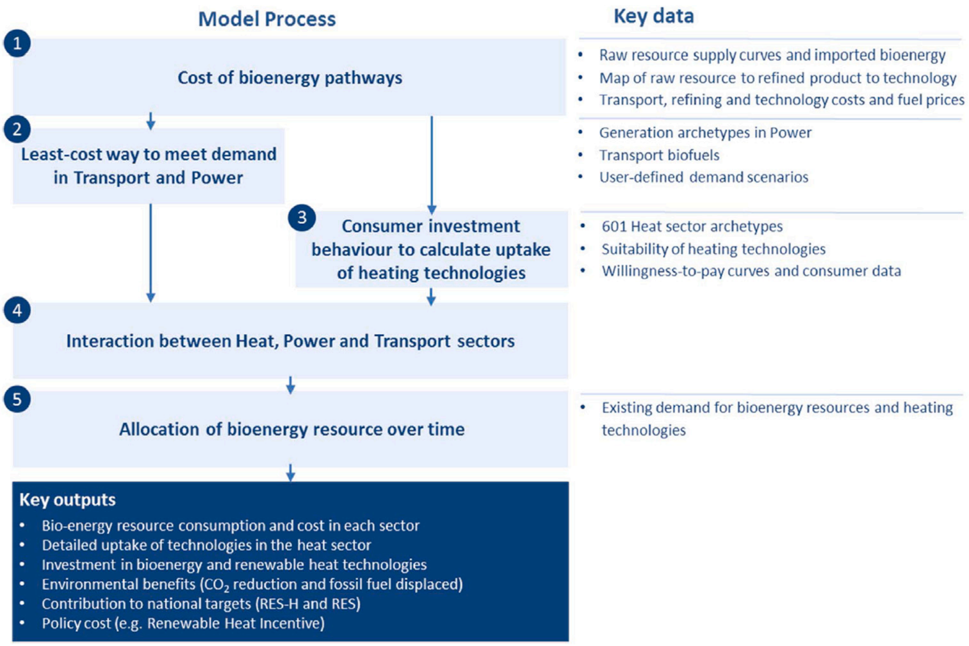

Fig. 1. Schematic structure of the BioHEAT model [16].

ranking for power, transport and heat (5) allocating biomass resources over time conditional on resource limitations, technology parameters, the priority ranking and support schemes, if any. Key outputs include consumption and costs of biomass resources, heat output by low-carbon technologies, and investments in low-carbon technologies. In BioHEAT, heat users in residential, commercial, public sector and industry can choose from a range of renewable and conventional technologies including: ASHP (air source heat pump), GSHP (ground source heat pump), WSHP (water source heat pump), biomass boiler, biomasss CHP (combined heat and power), geothermal, and gas, oil, solid fossil (i.e. combination of peat and coal) and electricity alternatives.

Focusing on the uptake of advanced heating technologies, six measures in BioHEAT help to capture risks and uncertainties associated with a specific type of technology or heat-user. The measures include: (A) using a detailed representation of the building stock, (B) including hidden monetary costs in the payback calculation, (C) including budget constraints, (D) incorporating decision-making frequency, (E) and the percentage of laggards, plus (F) using a payback analysis including heat-users' willingness-to-pay curves. The row elements of Table 1 are reproduced in Table 2 with the corresponding modelling measures (A)–(F) used to represent barriers faced by use sectors. In practice specific barriers are likely to be impacted by multiple measures, but Table 2 only illustrates the predominant measure corresponding to each barrier listed in Table 1.

Table 2
Measures to incorporate barriers in BioHEAT.

Barriers	Measures
Heterogeneity	A. Detailed representation of the building stock
Hidden costs	B. Hidden monetary cost
Access to capital	C. Budget constraints
Risks	F. Discounted payback calculation
Imperfect information	E. Percentage of laggards
Split incentives	A. Detailed representation of the building stock
Adverse selection	D. Decision-making frequency
Principal–agent relationships	F. Discounted payback calculation
Bounded rationality	F. Discounted payback calculation
Form of information	D. Decision-making frequency
Credibility and trust	D. Decision-making frequency
Inertia	E. Percentage of laggards
Values	E. Percentage of laggards
Power	E. Percentage of laggards
Culture	E. Percentage of laggards

Detailed representation of the building stock — Each building has its own unique set of physical conditions, while each decision-maker has a unique set of preferences, all of which influence the choice of heating technologies. Based on national representative surveys, BioHEAT uses national building typologies representing building stocks of each heat-user sector. There are in total 601 building archetypes: 124 in commercial sector, 52 in public sector, 112 in residential sector, 303 in industrial sector, and 10 in agricultural sector.[4] The matrix is characterized by features such as: type of activities/heating purposes, building ownership, age and size, heating requirements, insulation conditions, fuel types. These features are key determinants of energy demand, and moreover may significantly influence heat users' technology choices [25,66].

Hidden monetary cost — Hidden costs are captured in monetary terms and included in the payback period calculation of investors. The costs consist of both fixed and marginal costs, and vary by technology and heat users. Hidden costs are deemed to capture barriers such as space requirement for fuel storage, long-term maintenance costs associated with fuel deliveries, and hassles and costs related to retrofit, metring, auditing and others. For example, the upfront fixed hidden cost for biomass boiler ranges from €3,619–2,612,060 depending on the building archetype; For air-source heat pump, fixed hidden cost ranges from €0–1,487,291. Further explanations and assumptions regarding the hidden costs are listed in the table in the appendix.

Budget constraints — Budget constraints facing decision-makers can limit the uptake of renewable heating technologies unless external policy supports are in place. In BioHEAT, budget constraints are set by building archetype. For example, 7% of small commercial companies with self-owned buildings are assumed to have no budget to install advanced heating systems.

Decision-making frequency — Decision-making frequency reflects the time period after which heat-users make purchasing decisions, and

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[4] The input data of BioHEAT, such as the information on building stocks and hidden costs, are derived from the Irish building and heat sector survey that is a part of the "Unlocking the Energy Efficiency Opportunity" study [65].

is closely related to the type and status of existing heating technologies used by investors. Heat-users may only consider replacement of existing heating systems when it reaches end-of-life or there is a major renovation. The model assumes, for example, on a yearly basis 7% of commercial heat-users using gas or oil boilers will make decisions on future heating options.

Percentage of laggards — Heat-users may be reluctant to adopt renewable heating technologies due to imperfect information, inertia or other factors. A share of laggards is predetermined in BioHEAT, indicating that a percentage of decision-makers will not take action unless policy incentives are in place. For example, for commercial buildings percentage of laggards ranges from 18% to 59%.

Payback calculation — Payback periods of heating technologies are calculated and assessed against heat-users' willingness-to-pay curves to eventually decide on technology adoption. Willingness-to-pay curves are sector-specific (commercial, public, residential-owner-occupied, residential-private-landlord, industry), and derived using the data from representative surveys of the Irish heating market. For a technology with 5-year payback period, commercial building heat users have the highest willingness-to-pay as compared to public building heat users, industry and residential heat users.

3.2. Payback calculation and discounting

Payback analysis is a common analytical tool used by business, especially for small investments because of its simple nature [41,67,68]. A simple payback calculation is given in Eq. (1). Subscript i denotes a type of renewable heating technologies, whereas subscript j denotes a type of conventional substitute technologies that use gas or oil. Parameters C_i and C_j represent the upfront capital costs of renewable and conventional technologies respectively. Parameter H_i denotes the hidden cost of technology i and varies across investor groups. Annual maintenance costs O_i and O_j are assumed constant across years for a specific technology, but fuel costs F_i and F_j vary for different technologies across the lifetime. Essentially the formula is the difference in capital costs divided by the difference in operating costs. Renewable heating technologies are assumed to have higher capital costs than conventional options, and make savings on reduced maintenance costs in the following years. A shorter payback period is preferred by investors as it indicates that the project will pay for itself faster. If conventional technologies have lower maintenance costs than renewable technologies, i.e. the denominator is negative, investors adopt conventional technologies by default.

$$P_i = \frac{C_i + H_i - C_j}{O_j + F_j - (O_i + F_i)} \tag{1}$$

P: payback period in years
C: upfront capital cost in €
H: hidden cost in €
O: annual maintenance cost in €/year
F: annual fuel cost in €/year
i: heating technology
j: pre-existing heating technology

A significant drawback of the simple payback calculation is the lack of consideration regarding the time value of money due to opportunity cost. The payback calculation in BioHEAT is therefore modified using the following two methods: (1) adjust the capital expenditure by the minimum required rate of return, and then follow the usual steps of calculating the payback period; (2) discount future cash inflows, and then follow usual steps of calculating the payback period. In either way, the discounted payback period will be longer than the simple payback period.

The first approach is to adjust the numerator with the minimum acceptable rate of return on capital investments. The minimum acceptable rate of return, or hurdle rate, is widely used by energy utilities for investment appraisal. The underlying intuition is that the investor will only choose advanced heating technologies over conventional options if the additional investment yields a minimum acceptable return given the perceived opportunity cost of forgoing other projects. The ratio between the expected return of the investment (numerator) and the fixed annual repayment (denominator) is the duration required. The equation of the discounted payback is given by:

$$DP_i^1 = \frac{(C_i + H_i - C_j) \times N \times \frac{r(1+r)^N}{(1+r)^N - 1}}{O_j + F_j - O_i - F_i} = P_i \times N \times \frac{r(1+r)^N}{(1+r)^N - 1} \tag{2}$$

where r is the minimum acceptable rate of return on capital investments, and N is the lifetime of heating technologies in years. The second approach is to discount future cash inflows to the present value considering both the risk and time value of money. The future cash inflows, namely the periodic saving from reduced maintenance costs, are netted against the initial investment outflow, until it finds the point at which the sum of the periodic inflows equal the initial outflow. The equation is given by:

$$DP_i^2 = ln\left(\frac{1}{1 - \frac{(C_i + H_i - C_j) \times r}{O_j + F_j - O_i - F_i}}\right) \Big/ ln(1+r) = \frac{-ln(1 - P_i \times r)}{ln(1+r)} \tag{3}$$

An example is given below to highlight the substantial difference between simple payback and discounted payback calculations. A heat user considers a ground source heat pump over an oil boiler with a 7% discount rate. The technology has a 25 year lifetime, and requires additional capital expenditure of €15 000. Compared to an oil boiler, a ground source heat pump is expected to save €1500 annually in maintenance and fuel costs. The simple payback period equals 10 years according to Eq. (1), the discounted payback using the first approach is 21.5 years, and the discounted payback using the second approach is 17.8 years. Fig. 2 depicts the simple payback period (solid line), the first discounted payback approach (DP_i^1, shot-dash line), and the second discounted payback approach (DP_i^2, long-dash line). Given discount rate r and technology lifetime N, DP_i^1 is a linear mapping of the simple payback P_i, while DP_i^2 is a non-linear mapping with DP_i^2 less than $< DP_i^1$ until the two mappings coincide, i.e. $DP_i^1 = DP_i^2$, at approximately 25 years when $P_i = 11.7$. In this one example the implementation of the payback calculation is between 78% and 115% higher than the payback calculation in Eq. (1), and although just one step in modelling a technology adoption decision, illustrates the risk of using simplified modelling conventions.[5] After the payback calculation the payback years required by a heating technology is compared to investors' willingness-to-pay (WTP) curves to find the percentage of investors that are willing to invest. Representative surveys suggest that the vast majority of heat users only accept technologies with a payback period of less than 10 years [16].

Regarding the value of the rates, we use a default 7% discount rate, for example, for heat pump technologies, and a 5% risk premium added for biomass technologies because of the supply chain risks of biomass fuel.[6] Table 3 lists all the sectors and low-carbon technologies

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[5] An underlying assumption of DP_i^2 is that the periodic cash inflow must be greater than the interest of the initial investment. That means $\frac{(C_i+H_i-C_j)\times r}{O_j+F_j-O_i-F_i}$ must be smaller than one in Eq. (3); otherwise the investment would not happen in the first place, and a heat user would choose conventional options by default. In Fig. 2 this corresponds to the fact that DP_i^2 is undefined for x ranging above 14.29.

[6] Production of bioenergy requires biomass inputs and the feedstock supply is subject to seasonal variations. Extreme weather events such as prolonged droughts and heatwaves can impact the yield of grass and forestry residues. Moreover, if biogas plants rely on grass and manure collected from local farmers, the feedstock supply can experience seasonal fluctuations with lowest stocks in the late spring which may influence the supply of biomass fuel in short term. If large amounts of feedstock are imported, trade related issues such as taxations and export restrictions can lead to price volatility and even feedstock outage. Investors in bioenergy sectors perceive these potential supply risks and this is incorporated via discounted levelised costs in power and transport supply, and via discounted payback period in heat supply.

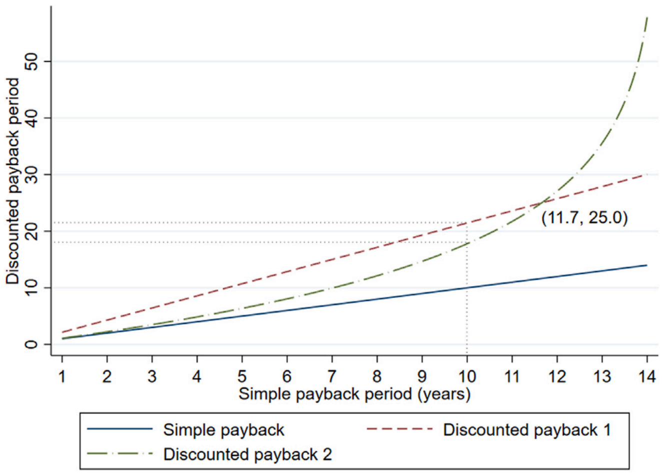

Fig. 2. Discounted payback periods of an investment on a ground source heat pump. Note: The payback periods reflect an investment consideration of a ground source heat pump over an oil boiler subject to a discount rate of 7%. Heat pump is assumed to have a 25 year lifetime, requires additional capital expenditure of €15 000, but will save €1500 annually in maintenance and fuel costs compared to an oil boiler.

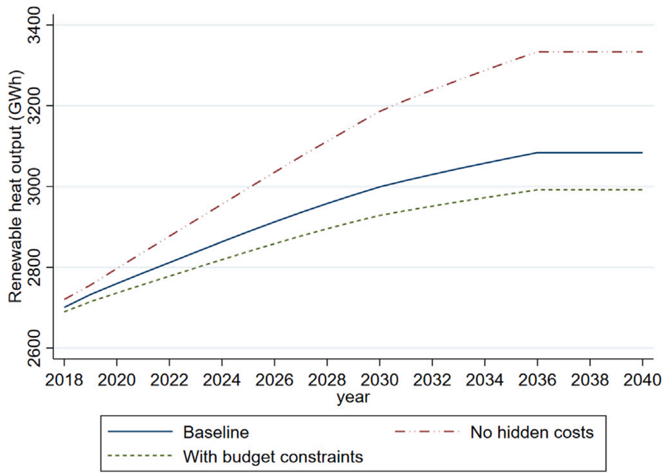

Fig. 3. Renewable heat output under alternative assumptions. Note: Lines show the renewable heat projections of low-carbon technologies under baseline conditions (solid line), baseline conditions but without hidden costs (dash-dotted line), and baseline conditions but with budget constraints (dotted line).

Table 3
Renewable heat technologies.

Sectors	Technologies	Rates
Commercial	Biomass boiler, Biomass CHP ASHP, GSHP, WSHP, Geothermal	12% 7%
Public	Biomass boiler, Biomass CHP ASHP, GSHP, WSHP, Geothermal	12% 7%
Industry	Biomass boiler, Biomass CHP ASHP, GSHP, WSHP, Geothermal	12% 7%
Residential	Biomass boiler, Biomass CHP ASHP, GSHP, WSHP, Geothermal	12% 7%
Agriculture	AD CHP	12%

Note: The table lists all the low-carbon technologies and the heating demand sectors considered in BioHEAT. Rates for biomass technologies are collected from Durusut et al. [16]. Rates for heat pump technologies are collected from Chan and Lam [69], Kulcar et al. [70] and Aste et al. [71].

used in the scenario analysis of the present study. There are numerous discounting rates documented in the literature, especially in studies involving investment evaluation for low-carbon electricity generation technologies as well as investment decision making for energy efficiency measures. Although there is no ‘right’ discount rate, a 7% discount rate is not incongruous. For example, Chan and Lam [69], Kulcar et al. [70] and Aste et al. [71] conduct financial assessments of heat pumps and use a discount rate of 7%, whereas Durusut et al. [16] employ discount rates of 5%, 7.5% and 10% to evaluate high-efficiency co-generation and district heating and cooling in Ireland. Our rates are also in largely line with the rates used in the EU reference scenario 2016 for non-energy intensive industries, service sectors, and households [49]. In the next section we show that the small assumption on discounting can have a big impact in terms of likely model outcomes, and in the case of over-estimates of technology adoption will lead to a shortfall in achieving policy targets. That being said, the emphasis is on the importance of the discounting rules rather than recommending a universal rate that fits all.

4. Results

4.1. Total renewable heat output

The previous sections identify a series of behavioural barriers and the corresponding measures in BioHEAT. In the present section we demonstrate the impact of these measures on the deployment of renewable heating technologies. The baseline scenario is defined to be the situation that considers (A) the detailed representation of the building stock, (B) monetary hidden costs in the payback calculation, (D) decision-making frequency of 7% yearly, (E) laggards in each decision making year, but without (C) budget constraints and using (F) simple payback calculation. Furthermore, two variations of the baseline scenario are constructed. These include a cases where budget constraints are incorporated and secondly, a case without hidden costs in the payback calculation. It is noteworthy that the scenarios are chosen solely for illustrative purposes to show the methodological representation of behavioural factors in the decision making process regarding heating technologies. This paper does not seek to project the development of the renewable heat technology uptake in Ireland.

Fig. 3 presents the renewable heat output of the baseline scenario (solid line) jointly with the two variations (dashed lines). Under the baseline setting, renewable heat output rises steadily over time reaching a plateau after 2036. Without hidden costs, the uptake of renewable heating technologies are significantly higher than the baseline scenario where hidden costs are imposed. The difference in renewable heat outputs between the baseline and the scenario without budget constraints are relatively minor as reflected in Fig. 3. Table 4 describes the percentage changes per heating technology. Heat pump technologies seem to be affected the most by the consideration of hidden costs, which is likely due to the high upfront costs of heat pump technologies.[7] Overall, the renewable heat outputs in 2030 are projected to be 2999.12 GWH under the baseline scenario, 3185.90 GWH without hidden costs (+6.2%), and 2928.31 GWh with budget constraints (−2.4%).[8]

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[7] For example, ground-source heat pumps are one of the most popular renewable heating options, as they provide a reliable source of heat and have great energy savings potential [33,72]. However, the upfront costs of ground-source heat pumps can range from €17,000 to €28,000, depending on the size and area. Air-source heat pump costs are lower than that of ground-source heat pumps, with prices ranging from €12,000 to €18,000 for an average Irish home [73].

[8] Throughout the result and discussion section, we use projections in 2030 as the reference point, e.g., to calculate the percentage changes in the result section. The main reason of using the 2030 output as the reference point is that the heat output trajectories reach the ceiling before 2040 in all of the cases and the model assumptions are likely to be changed in 20 years’ time. Therefore, we prefer to use projection outcomes in nearer future for discussion.

Table 4
Percentage differences of renewable heat outputs compared to the baseline scenario.

	Biomass boiler	Biomass CHP	ASHP	GSHP	WSHP	Geo.
No hidden costs	2.73%	0	6.78%	18.25%	14.24%	−0.59%
With budget constraints	0	0	−3.56%	−9.64%	−9.89%	−1.58%

Note: The first row presents the percentage differences of renewable heat output in 2030 between the scenario without hidden costs and the baseline scenario; the second row presents the percentage differences of renewable heat output in 2030 between the scenario with budget constraints and the baseline scenario.

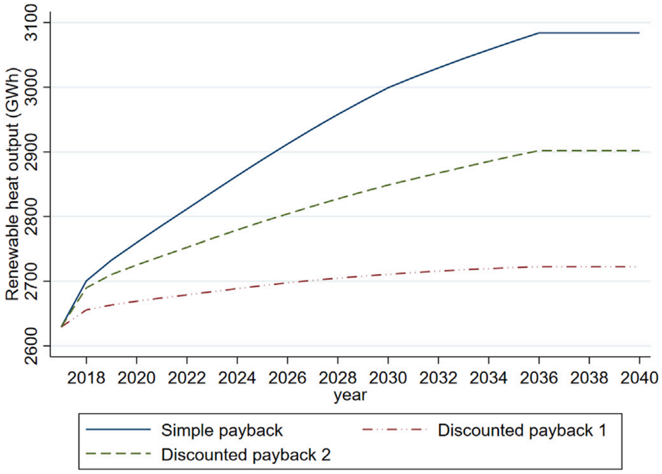

Fig. 4. Renewable heat output under alternative payback calculations. Note: Lines show the renewable heat projections of low-carbon technologies using simple payback calculation (solid line), and discounted payback calculations (dash-dotted line and dotted line).

Fig. 4 presents the total renewable heat generated by low-carbon technologies under three payback calculations. The solid line describes the baseline scenario with simple payback calculation, while the dashed lines indicate renewable heat output using discounted payback calculations. Overall, renewable heat output using simple payback calculation remains the highest over the three projections followed by the second discounting method, DP_i^2. Renewable heat output is projected at 2999 GWh, 2711 GWh (−9.6%) and 2849 GWh (−5.0%) in year 2030 under the three payback calculation assumptions.

4.2. Heat output by different low-carbon technologies

At the disaggregated level, heating technologies are affected to different extents by behavioural barriers. This section aims to identify the impact of discounting methods at the disaggregated level. Fig. 5 presents the heat output by individual low-carbon technologies in the baseline scenario (solid lines) and two discounting scenarios (dashed lines). With the simple payback calculation, the payback years of low-carbon technologies are relatively short, implying higher uptake rates of these technologies. Among the technologies, biomass boilers are the most popular option, contributing to the largest share of renewable heat output in a given year. Under the baseline scenario, heat output of biomass boilers reaches nearly 2140 GWh by year 2030 and stays constant afterwards. When considering the cost of capital and uncertainties, biomass boiler uptake yields about 2060 and 2080 GWh heat output using the first and the second discounted payback method, respectively. Compared to the baseline scenario, the magnitude of the impact associated with different discounting methods is minor, that is, a reduction of less than 100 GWh in 2030. However, the deployment of biomass boilers are substantially different between scenarios. Under the simple payback calculation, the uptake of biomass boilers grows each year reaching a maximum gross heat output in 2030. Under the two discounted payback methods the ceiling for biomass boiler deployments occurs almost immediately, and the gross heat output remains largely constant across the projection period.

Table 5
Percentage differences of renewable heat outputs compared to the simple payback calculation.

	Biomass boiler	Biomass CHP	ASHP	GSHP	WSHP	Geothermal
DP1	−3.67%	0	−32.21%	−29.53%	−9.67%	−98.09%
DP2	−2.88%	0	−10.85%	−20.77%	−7.46%	−73.16%

Note: The first row presents the percentage differences of heat production in 2030 using the discounted payback method 1 relative to the heat production using the simple payback calculation; The second row presents the percentage differences of heat production in 2030 using the discounted payback method 2 relative to the heat production using the simple payback calculation.

ASHP is the second largest source of heat generation after biomass boilers. Under the baseline scenario, heat output from ASHPs grows steadily, reaching its deployment ceiling of approximately 950 GWh in 2036. Heat generation from ASHPs under the two discounting scenarios follow a similar pattern as the baseline but reach lower deployment ceilings of 650 GWh and 850 GWh. For the other technologies the impact of payback calculation is even greater. As the uptake levels of these technologies are low at the baseline scenario, the consideration of uncertainties leads to nearly zero deployment of GSHP, WSHP and geothermal if the first payback discounting method is employed. Biomass CHP has a zero growth in uptake under all three scenarios. This is likely due to the limited suitability of this technology and the high upfront costs of biomass CHP. Table 5 shows the percentage differences of heat output under the two discounting scenarios compared to the baseline scenario. Overall, technologies that have lower deployment in the baseline scenario seem to be more sensitive to discounting methods. Projection results for the residential sector are presented here as well for the coherence of the results. As shown in Fig. 6, technology adoption in the residential sector is very marginal.

4.3. Cross-sector comparison

Fig. 6 illustrates the deployment of low-carbon technologies in four heating demand sectors under the baseline scenario and two discounting scenarios. Under the baseline scenario, industry has the highest uptake rate of low-carbon technologies, with nearly 1950 GWh heat generated by low-carbon technologies by 2040. The residential, commercial and public sectors have 785 GWh, 710 GWh and 65 GWh heating demand met by low-carbon technologies by 2040, respectively. Turning to the percentage changes as shown in Table 6, the projected uptake of renewable heat technologies by the residential sector is the least impacted by the choice of payback calculation method, with the difference in heat output less than 10 GWh, or less than 1% of the heat generation under the baseline scenario. A possible explanation is that the low-carbon technologies are least popular to residential users. Fig. 6 shows that, under the simple payback calculation, heat output of low-carbon technologies in residential sector rises by only 7 GWh in the long run, that is equivalent to less than 1% growth from the current level. This implies that the deployment of renewable heating technologies in residential sector is likely to be slow without further policy intervention.

Among the four heat-use sectors, the public sector sees the highest percentage growth in the deployment of low-carbon heating technologies, rising from zero to more than 60 GWh by 2040 in the baseline scenario. Meanwhile, Table 6 shows that the uptake of advanced heating technologies in public sector is also the most sensitive

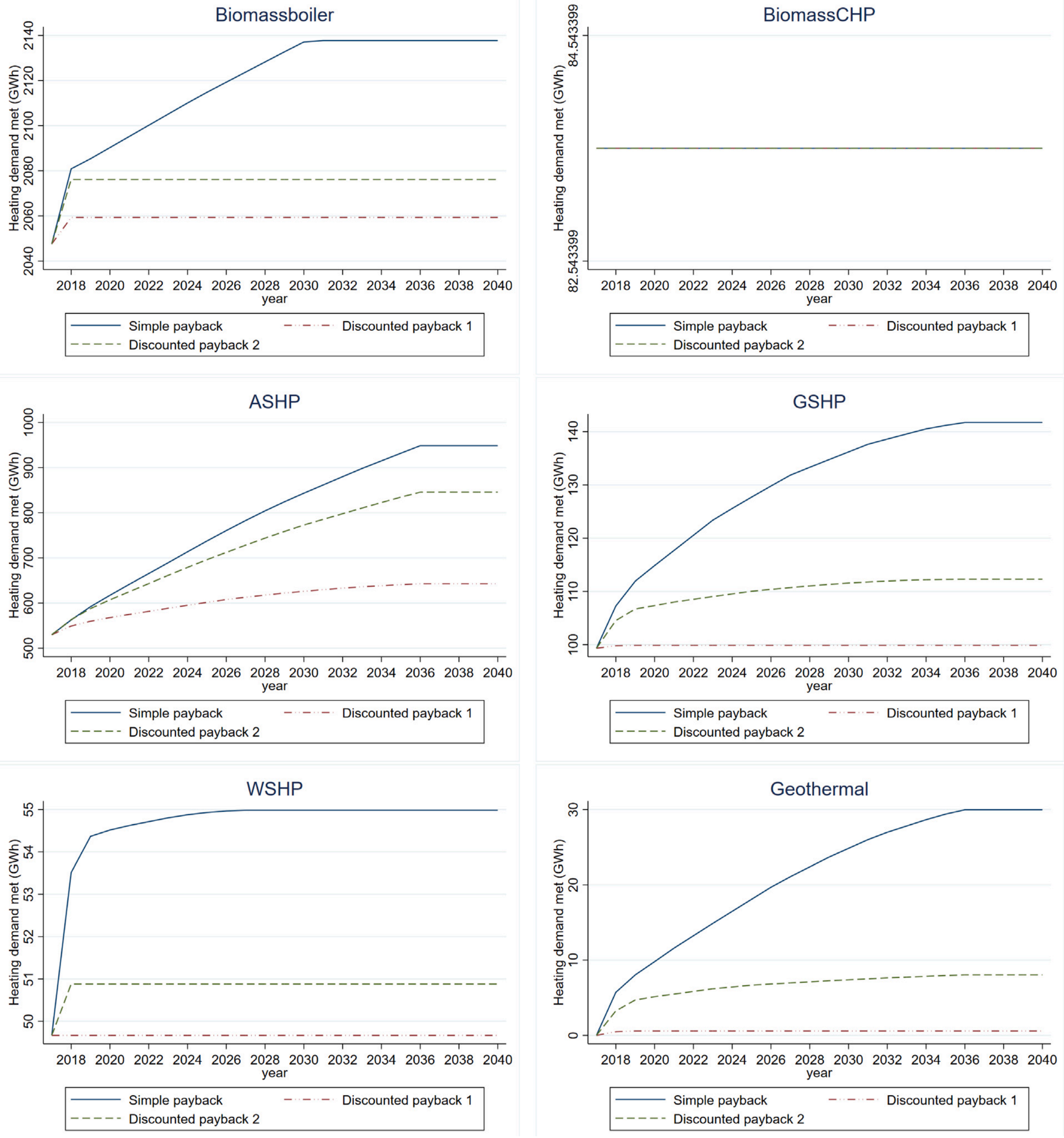

Fig. 5. Heating demand met by low-carbon technologies — by technology.

to discounting compared to other sectors. Heat output of low-carbon technologies in public sector drops by approximately 62% and 23% respectively using the first and the second payback discounting method. The projected uptake in the commercial and industrial sectors is also affected to some extent by the discounting methods. The gaps between the heat output under the baseline scenario and that under the discounted payback scenario (by 2030) are up to 30% and 10% for commercial sector and industry, respectively.

Table 6
Percentage differences of renewable heat outputs compared to the simple payback calculation.

	Commercial	Public	Industry	Residential
DP1	−29.35%	−61.76%	−10.22%	−0.87%
DP2	−11.97%	−23.45%	−5.81%	−0.55%

Note: The first row presents the percentage differences of heat production in 2030 using the discounted payback method 1 relative to the heat production using the simple payback calculation; The second row presents the percentage differences of heat production in 2030 using the discounted payback method 2 relative to the heat production using the simple payback calculation.

5. Discussion and conclusion

Typical energy models tend to under-represent or neglect multiple barriers to technology adoption in reality but focus on technological and economic conditions. A detailed representation of the decision making process is indispensable to modelling renewable technology adoption and relevant policy supports to tackle the barriers. Employing Ireland's techno-economic energy model, we provide a conceptual framework to integrate heat users' behaviour and decision-making process in the projection of renewable technology. By comparing variations

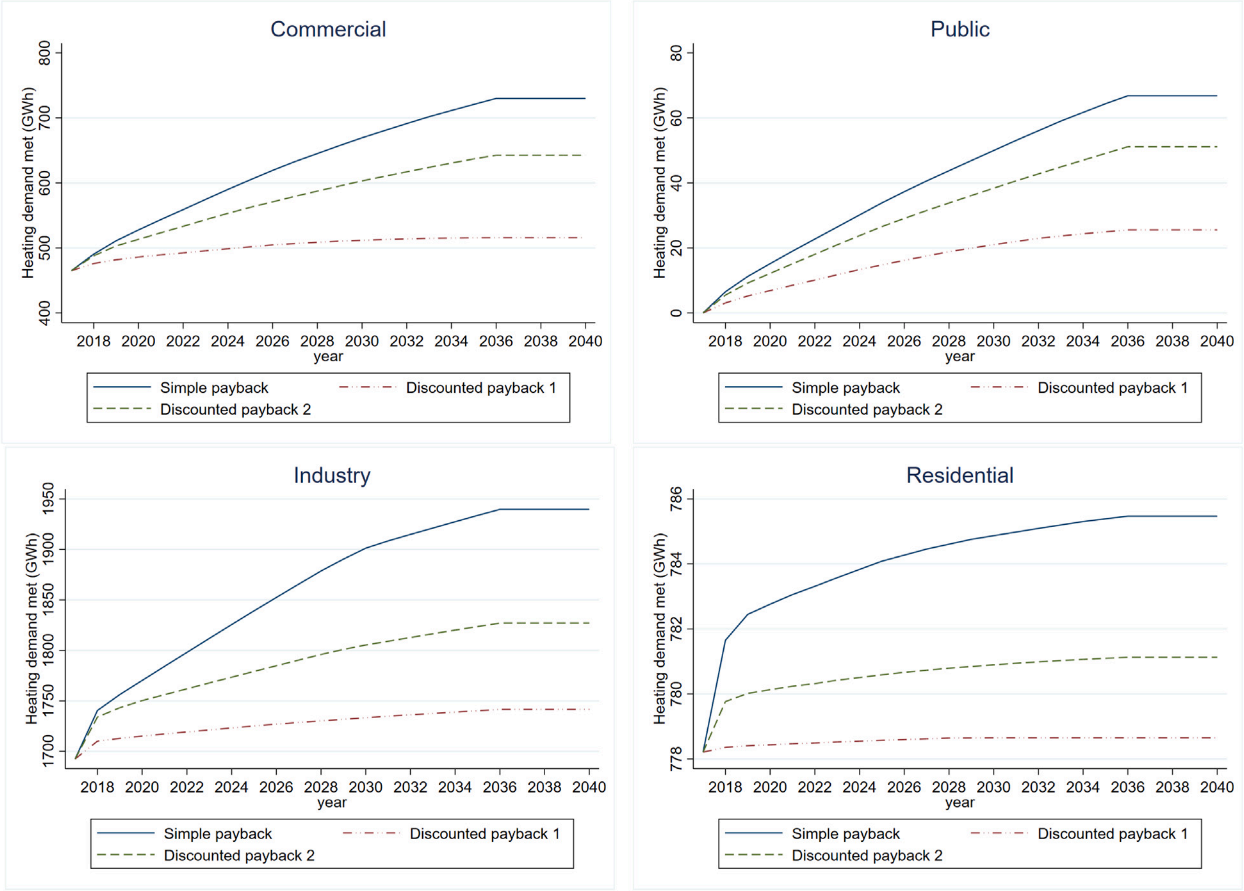

Fig. 6. Heating demand met by low-carbon technologies — by sector.

when considering certain barriers and varying discounting methods, we show that the inclusion of economic and behavioural barriers and the ways of representation have a significant influence on projections of renewable energy uptake. Overlooking these factors in national energy projections and plans can lead to significant overestimation of technology development, and consequently underestimation of the effort to reach carbon neutrality policy targets.

In the present study we employ six measures to capture in total 15 types of barriers summarized from existing literature. Our analysis reveals differences in the relative impact of renewable technology uptake depending on economic and behavioural barriers and how they are modelled. For example, we find that how budget constraints are modelled only have limited impact on projection results. The percentage change of renewable heat output after taking budget constraints into account is approximately 2.4% (Fig. 3, by 2030). This implies that the budget constraint may be a minor issue relative to other barriers in the decision making of Irish heat users. In other words, for sectors with a large share of heat users on tight budgets, the effectiveness of retrofit grants could be lower than expected in terms of facilitating additional energy efficiency investments. Therefore, our findings emphasize the importance of identifying the potential groups that are mostly likely to invest on advanced heating technologies in conjunction with policy supports.

Alternative discounting approaches with subjective rates have been shown to have substantial impacts on projection results. This explicitly underlines the importance of having a wide spectrum of economic and behavioural barriers embedded in energy systems modelling, and the necessity of clarifying the technical specifications. However, our results show that hidden costs can lead to a larger deviation from the baseline scenario than discounting methods do under certain circumstances. The percentage change of renewable heat output relative to baseline is approximately 6.2% (Fig. 3, by 2030) when monetary hidden costs are not considered, while the percentage change corresponding to our second discounting approach is about 5% (Fig. 4, by 2030). Our findings imply that, in terms of policy tools, one-off grants that subsidize the upfront costs (including hidden costs) may be more efficient in promoting technology adoptions than loan schemes that could help to reduce long-term uncertainties under certain circumstances.

In Sections 4.2 and 4.3 we compare projections across technologies and sectors using two discounting methods to the baseline using simple payback calculation. The impacts of various barriers are not uniform across technologies or heat user sectors. Our results suggest that biomass boilers are less affected by the measures than heat pump technologies. This may be associated with the mild growth of biomass boiler, which is roughly 4% between 2017 to 2030 in the baseline scenario. As the uptake maintains a slow-growth path, the deviation from the baseline led by different measures will also be limited. From a heat-user perspective, the public sector is the most sensitive to the choice of discounting compared to other sectors. The projected uptake of renewable heating technologies is the lowest in the residential sector, while it is also the sector least affected by discounting methods. This again highlights the importance of identifying the groups that are most likely to invest on low-carbon technologies, especially if public funds are limited.

Decarbonizing the heating sector can make significant contribution to EU's emissions reduction ambition. It also provides opportunities for energy diversification and improving energy security. It is challenging to decarbonize the heating sector because of its decentralized characteristics with investment decisions largely made at individual building level. A better understanding of human factors in decision making, and integrating these barriers into energy systems modelling are crucial to promote the low-carbon transition of heating sector. The present study provides several implications. First, this study empirically demonstrates the importance of modelling human behaviour and indirect costs to deploying technologies. The behavioural aspects are associated with a complex system consisting of cognitive, institutional and social-political components. Diverse approaches to capture these components beyond discounting are desired in future research to improve the model-based analysis of energy systems. Over-simplifying these components in energy systems models will contribute to high model uncertainty.

Second, our results show that without policy supports the deployment of low-carbon heat technologies is either slow (e.g. biomass boiler) or sensitive to perceived risk (e.g. heat pumps). This implies that financing commitments will play a role in scaling up proven technologies. Low-carbon system standards and tax credits, as well as cross-border regulations on sustainable fuels, will help stimulate demand and offer certainty to investors. A long-term outlook on the pace and scale of heating decarbonization with more direct evidence on how this could be achieved will be helpful to raise public awareness and acceptance of the transition. Third, this study calls for more attention to be devoted in heat decarbonization among industry and commercial heat users. Compared to private households, industry and commercial heat users are likely to have better access to capital and higher willingness to adopt advanced heating technologies. The potential of biomass heating technologies has not been fully recognized in existing literature, especially among small and medium sized commercial users. Large-scale infrastructures such as waste-based CHP plants and district heating add additional options to heat decarbonization, and may prove easier to deliver than an end-to-end approach.

Our study has some limitations. First, due to limited knowledge on other representative energy systems models, we are unable to conduct cross-model comparison exercises to show the influence of the same barrier under different modelling environment. Second, the assignment of the measures to existing barriers is based on technological realizability and the understanding of the literature on the barriers to energy efficiency measures. This emphasizes that the barriers mentioned in the present study is a non-exhaustive list and it is not possible to model each barrier separately (e.g. the long-standing challenge in adequate and timely support in providing and installing technologies). Some of the measures we employ are embedded in the input data derived from national building surveys, so it is not possible to present all the parameters and values in the present study. In this respect, there is still a lot of space remaining for improvement and future work in the realism of behavioural factors in energy systems modelling. Meanwhile, as our results suggest the deployment of renewable heating technologies is subject to various barriers to energy efficiency investments, these barriers and the integration approaches in energy models could have implications on total CO2 emission projections, and should be taken into account when governments set heat-related climate action plans. Extended measures and prioritization may be desired to decarbonize the heating sector in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Table A.1
Assumptions of hidden costs.

Hidden cost	Explanation	Assumption
Metring	The additional capital cost of the heat meter	Cost varies with size (€4–6/kWth)
Biomass storage unit	The additional capital cost of the biomass fuel storage unit (for biomass only)	Cost varies with size
Space for biomass fuel storage unit	Compensation for loss of space used for the fuel storage unit (for biomass only)	Cost varies with sector; Public/Commercial: €488/kWth (€975/m2); Industry: €163/kWth (€325/m2)
Administration costs	Compensation for the additional administration time required for the renewable technology	Costs vary with sector and technology type
Energy audit	Cost for having an energy audit carried out	Cost varies with building size: €0.67/m2
Grid connection	Fee for grid connection (for CHPs only)	Cost varies with size: €200 k–€1 m
Retrofit of emitters	Additional capex and installation costs for installing radiators where required (or replacing existing radiators with large area radiators or underfloor heating for heat pumps)	€625/kWth (not required for new buildings)
Decommissioning the pre-existing technology	The cost of removing the pre-existing technology	Marginal cost: €12/kWth if applicable: most stakeholders suggested that the pre-existing option would be left in place as a back-up so this cost is not included in the calculation

Appendix

See Table A.1.

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